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NONLINEAR BOUNDARY LAYER RECEPTIVITY WITH HIGH-AMPLITUDE NOISE

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ABSTRACT

A typical turbulent flow produces skin-friction and heat-transfer levels that are an order of magnitude higher than that corresponding to laminar flow. In flight, control of skin friction is important for energy-efficient operation. In gas turbine engines, prediction of the onset of turbulent flow is critical for prediction of the heat transfer on turbine blades. Gas-turbine flows are characterized by high-amplitude freestream noise and turbulence in contrast to the flight environment, which typically has very low turbulence levels. It is not clear how to define these disturbances except to say that they can be decomposed to a vortical part (turbulence) and an irrotational part (noise).

Disturbances in the freestream enter the boundary layer as small fluctuations of the basic state and excite unstable modes. The receptivity stage of the transition process is the least understood, but is extremely important because it provides the initial condition on the disturbance amplitude. Here we consider disturbances consisting of only plane acoustic waves. We ignore freestream turbulence and artificial disturbances within the boundary layer. Moreover, the main objective of this experiment is to isolate the influence of the leading edge on the initial amplitudes of T-S waves and to determine the limit of linear receptivity for 2-D roughness. The goal is to establish the framework for the active control of such fluid motions and to provide the initial conditions for computational and analytical modeling.

EXPERIMENTAL PROCEDURES

These experiments are conducted in the ASU Unsteady Wind Tunnel whose details are given by Saric (1992). A well-designed contraction cone, honeycomb, and seven screens follow the guidelines of Reshotko et al. (1997). Details of the present experimental work are given in Saric & White (1998). Each end of the flat-plate model is machined with a unique leading edge. One is a 20:1 modified super ellipse (MSE) and the other is a 40:1 MSE. The MSE shape was formulated and used by Lin et al. (1992) and Fuciarelli et al. (1998) in a DNS of the receptivity problem. This shape eliminates the curvature discontinuity at the ellipse/flat-plate juncture and moves the minimum pressure region toward the leading edge. Without roughness, receptivity is limited to the leading edge.

The acoustic disturbances are introduced by a set of nine speakers located on the plenum wall. The sound pressure level in the test section can vary from 90 dB to 127 dB. At this upper level u'_∞ approaches 1% U_∞. The incidence angle and amplitude of the sound wave are measured by 20 microphones placed in the walls at the leading-edge location. The relative phase measurements show an essentially plane sound wave at zero incidence.

The typical boundary-layer hot-wire signal at the driving frequency is composed of the T-S wave, the Stokes wave within the acoustic boundary layer, and the probe vibrations. A new technique is implemented to measure the amplitude of the T-S wave. From linear theory, the maximum of the T-S wave propagates at approximately one third the speed of the freestream speed. Using this fact, the traveling T-S wave can be isolated from the acoustic disturbance and associated Stokes wave by sending bursts of sound into the test section. The initial sound burst is first measured and after the sound wave has passed, the slower-traveling T-S wave initiated by the sound burst is measured. Using this idea, bursts of sound are generated with a time interval between bursts long enough for the acoustically-forced T-S wave to pass the hot wire before another sound burst is emitted. Figure 1 shows a time trace depicting the sound-burst wave sensed by both wires and the trailing T-S wave measured by the boundary-layer wire for $R = 1140$, $F = 56 \text{ X } 10^{-6}$, $f = 80$ Hz, and $\hat{x} = 1.8$ m. An ensemble average of the bursts (typically 40) is taken to account for any low-frequency oscillations in the test section and to minimize error. This technique is useful for noise and large amplitude signals. Figure 2 shows a T-S wave profile obtained with this method and its comparison with the solutions of the Orr-Sommerfeld Equation (OSE). The agreement between theory and experiment indicates we have a viable technique.

LEADING-EDGE RECEPTIVITY

The data of Saric et al. (1995) showed a very narrow pass-band of receptive frequencies. This was behavior not predicted by analysis (Kerschen et al. 1990) or computation (Fuciarelli et al. 1998) and was at odds with Orr-Sommerfeld Equation (OSE) results. Detailed measurements showed that the continuous, phase-correlated sound signal was forcing a resonance in the wake causing an asymmetric oscillation, which fed back to the leading edge in the form of fluctuations transverse to the leading edge. This obviously biased these experiments.

For the new experiments, continuous white noise input was placed in the freestream. Figure 3 is a spectrum of the freestream and boundary-layer response. The agreement between the boundary-layer response and OSE shows that when the phase information is destroyed, wake resonance cannot occur and the leading-edge receptivity passband is congruent with the OSE passband for T-S waves. This confirms the problems Saric et al. (1995) had with wake forcing. Figure 4 is a summary of the results from the 20:1 leading edge at the 8 m/s condition using the pulsed sound technique. The pulsed technique essentially measures the T-S wave before the sound interacts with the trailing edge, giving a band of amplified T-S waves that is broader than Saric et al. (1995). Thus, all previous receptivity experiments need to be re-evaluated in the light of this new information.

A comparison with receptivity theory is done for the case of the 20:1 MSE and $F = 84 \text{ X } 10^{-6}$. These conditions represent the lowest Reynolds number that can be done with the experiment and highest Reynolds number that can be handled by the DNS. The DNS of Fuciarelli et al. (1998) shows Branch I receptivity $K_s = 0.048$ as compared with the experimental value of 0.05 in Figure 4. The agreement is quite good and lends evidence that the pulsed technique is the only reliable method.

2-D ROUGHNESS RECEPTIVITY

The receptivity of 2-D roughness is done in order to extend the work of Saric et al. (1991) and Kosorygin et al. (1995) to the nonlinear sound range. Saric et al. (1991) presented receptivity data at a fixed sound pressure level (90 dB) and showed nonlinearity with roughness height. Figure 5 presents T-S wave amplitude as a function of freestream sound amplitude. This is single sine-wave forcing over a 45 μm, 2-D roughness located at $x = 0.62$ m. Measurements taken at $U_\infty = 12.75$ m/s, $x = 1.60$ m, $f = 75.8$ Hz, $F = 50 \text{ X } 10^{-6}$. Since large-amplitude sound in the freestream may itself contain harmonics of the fundamental, the appearance of harmonics within the boundary layer is not prima facie evidence of nonlinear receptivity. Therefore, the departure of normalized T-S amplitude from a constant value is the indicator of nonlinearity provided the mean boundary-layer velocity has not changed. Thus, Figure 5 shows departure from linearity at 110 dB. Also shown is the local mean boundary-layer velocity normalized with the freestream. It remains constant so the boundary layer is still laminar and hence the departure of the normalized T-S amplitude from a constant value is nonlinear receptivity. Figure 6 has the spectra from the last three points in Figure 5; it is clear that the spectra are laminar.

We still see departure from linearity at 110 dB but now we see the departure from laminar flow (transition) at 117 dB. The data of Figures 5-8 were taken with continuous sound and a fixed wire but they have been verified using the pulsed technique.

There appears to be no basic difference between broadband and single frequency waves except that an order of magnitude increase in power is required over the broad band to achieve similar transition results of a single-frequency wave. However, the following sequence of figures (Figures 9-12) shows the nonlinear and transitional influence of the broadband input. Disturbance amplitude and mean velocity versus freestream sound pressure level are shown. White-noise forcing with 20-150 Hz bandpass over 45 μm, 2-D roughness at $x = 0.62$ m. Measurements taken at $U_\infty = 12.75$ m/s, $x = 1.60$ m. In these measurements, 2-D strips are doubled and then placed one T-S wavelength downstream. The basic roughness size is 45 μm. The use of the four combinations of roughness elements, (45, 0), (90, 0), (90, 45), and (90, 90), is still in the linear range since it has been shown that the addition of a roughness element one T-S wave downstream is linear superposition. Thus, the receptivity can be increased without approaching the nonlinear threshold of roughness height. One can see from Figures 9-12 that the nonlinear regime of disturbance amplitude occurs at lower sound amplitude and that transition (as measured by the mean velocity) moves forward. At sound pressure levels up to 125 dB, no bypass was observed. However, the database for theoretical models has been enhanced for both the nonlinear onset and transition location.

CONCLUSION

Leading Edge Receptivity

The sharp focusing of a single acoustic wave (Saric et al. 1995) is due to complicated duct acoustics. The correct measurements are made with sound pulses that are conditionally sampled. The actual receptivity coefficients are different and more broadband - consistent with DNS and OSE. Agreement between theory, DNS, and experiments is good when results are extended to Branch I.

Broad Band versus Single Mode

It is shown that there is little difference between the single-frequency excitation and white noise in that the amplitude of the individual mode still keenly triggers the response. Thus a single frequency at 120 dB is more dangerous than white noise at 120 dB where the energy is distributed across many modes.

Nonlinearity

Leading-edge receptivity is much weaker than 2-D roughness and hence no nonlinearity is observed. Receptivity of 2-D roughness departs from linear behavior at freestream levels of 110 dB for single-mode excitation. Breakdown is via the subharmonic. No bypass observed for freestream sound levels up to 127 dB (present limit of facility).

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REFERENCES

FUCIARELLI, D., REED, H. and LYTTLE, I. 1998 DNS of leading-edge receptivity. *AIAA-98-2644.*

KERSCHEN, E.J., CHOUDHARI, M. and HEINRICH, R.A. 1990 Generation of boundary instability waves by acoustic and vortical freestream disturbances. *Laminar-Turbulent Transition, Vol. III*, Eds. D. Arnal and R. Michel, Springer-Verlag.

KOSORYGIN, V.S., RADEZTSKY, R.H., Jr. and SARIC, W.S. 1995 Laminar boundary layer sound receptivity and control. *Laminar-Turbulent Transition IV*, Ed. R.Kobayashi, Springer.

LIN, N., REED, H.L. and SARIC, W.S. 1992 Effect of leading edge geometry on boundary-layer receptivity to freestream sound. *Stability, Transition and Turbulence*, eds. M.Y. Hussaini, A. Kumar, C.L. Streett, Springer-Verlag, New York.

RESHOTKO, E., SARIC, W.S., NAGIB, H. 1997 Flow quality issues for large wind tunnels. *AIAA-97-0225.*

SARIC, W.S. 1992 The ASU transition research facility. *AIAA-92-3910.*

SARIC, W.S., HOOS, J.A. and RADEZTSKY, R.H. Jr. 1991 Boundary-layer receptivity of sound with roughness. *Boundary Layer Stability and Transition*, FED-Vol. 114, Eds:D.Reda,H.Reed,R.Kobayashi,ASME.

SARIC, W.S., WEI, W., RASMUSSEN, B.K. and KRUTCKOFF, T.K. 1995 Experiments on leading-edge receptivity to sound. *AIAA-95-2253.*

SARIC, W.S. and WHITE, E.B. 1998 Influence of high-amplitude noise on boundary-layer transition to turbulence. *AIAA-98-2645.*

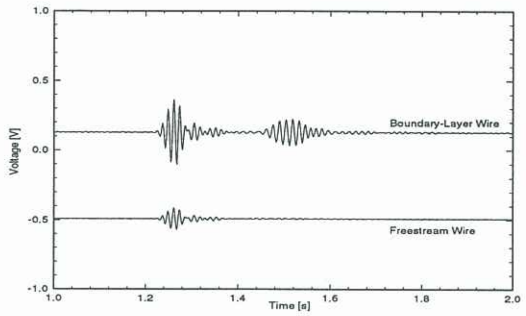

Figure 1. Time traces of freestream hot wire and boundary-layer hot wire for sound burst.

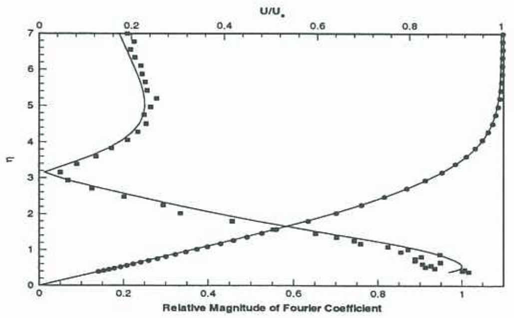

Figure 2. Comparison of measured mean-flow and disturbance flow with theory. 2D roughness at 90 μm. 100 averages with pulsed technique. $R = 1051$, $F = 60 \text{ X } 10^{-6}$.

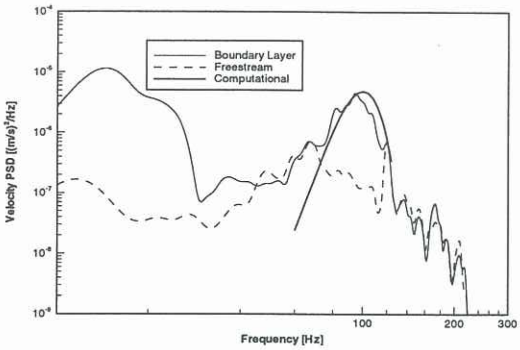

Figure 3. Spectrum of white noise in free-stream, boundary-layer response, and OSE spectrum. Leading edge receptivity only.

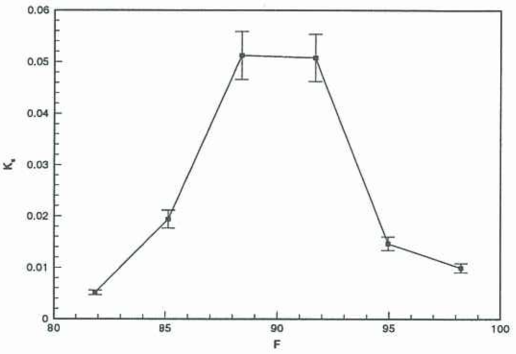

Figure 4. Receptivity coefficient, K_s, for $U_\infty = 8$ m/s.

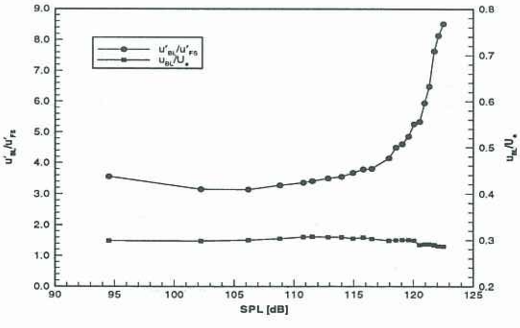

Figure 5. Disturbance amplitude and mean velocity versus freestream sound pressure level. Sine-wave forcing over 45 μm, 2-D roughness at $x = 0.62$ m. Measurements taken at $U_\infty = 12.75$ m/s, $x = 1.60$ m, $f = 75.8$ Hz, $F = 50 \text{ X } 10^{-6}$. Conditions of Saric et al. (1991).

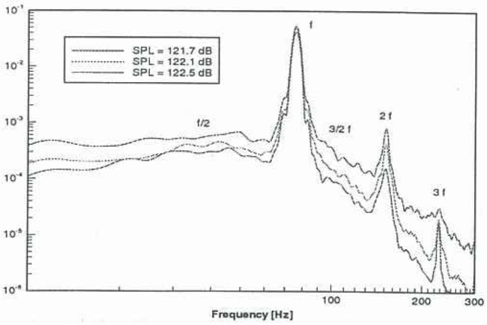

Figure 6. Spectra of last three points of Figure 5.

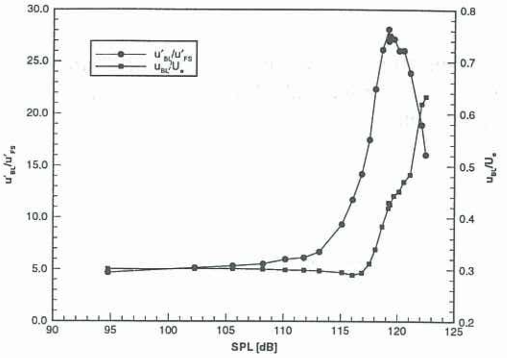

Figure 7. Same as Figure 5 except measurements taken at $x = 1.80$ m.

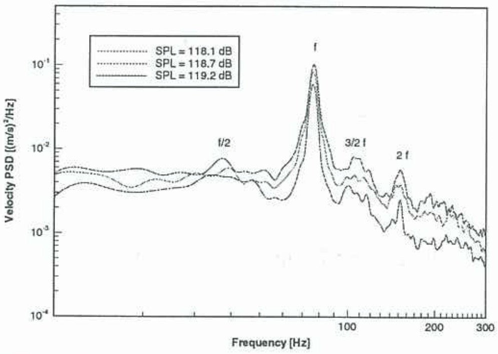

Figure 8. Spectra of three points near maximum amplitude of Figure 7.

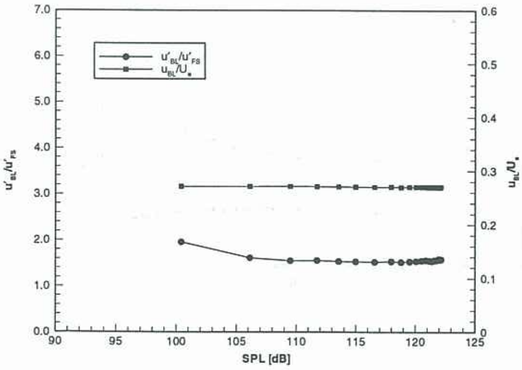

Figure 9. Disturbance amplitude and mean velocity versus freestream sound pressure level. White-noise forcing with 20 - 150 Hz bandpass over 45 μm, 2-D roughness at x = 0.62 m. Measurements taken at U_∞ = 12.75 m/s, x = 1.60 m.

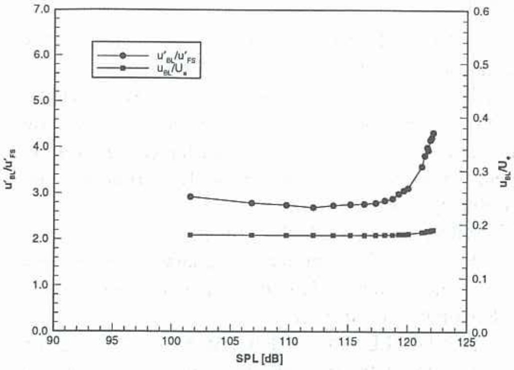

Figure 10. Same conditions as Figure 9 except 90 μm roughness at x = 0.62 m.

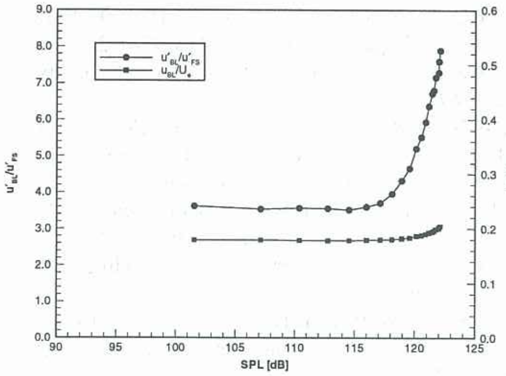

Figure 11. Same conditions as Figure 9 except 90 μm roughness at x = 0.62 m and 45 μm roughness at x = 0.67 m.

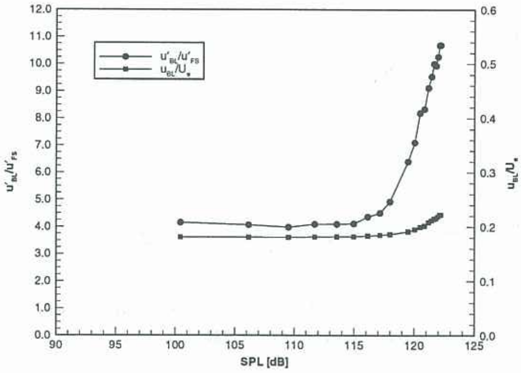

Figure 12. Same conditions as Figure 9 except 90 μm roughness at x = 0.62 m and 90 μm roughness at x = 0.67 m.